NOAA Technical Memorandum NWS SR-149

RADAR DIAGNOSTIC PARAMETERS AS INDICATORS

OF SEVERE WEATHER IN CENTRAL FLORIDA

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Fort Worth, TX

June 1993

UNITED STATES

DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration

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ABSTRACT

Diagnostic techniques based on WSR-88D radar observations and sounding data are needed to assess severe storm potential in Florida's semi-tropical thunderstorm environment. To begin this effort, nearly 100 severe weather events involving hail 3/4 in (1.9 cm) or greater in diameter, thunderstorm wind gusts 50 kt (26 m/s) or greater, or tornadoes were examined, along with RADAP II reflectivity and VIL (Vertically Integrated Liquid) observations. RADAP II algorithms are similar to those which will be employed with the WSR-88Ds. Several other parameters, including (a) cell density (VIL divided by echo top), (b) cell momentum (VIL [mass per unit area] multiplied by storm velocity produces a quantity proportional to momentum and will be referred to as momentum for this study), and (c) echo top growth rates were calculated for comparison with severe storm reports. In addition, a formula for hail detection was derived to represent processes responsible for different types of severe weather.

Tornadoes are classified by the method of formation as stretched vortex, gust induced or dynamic. Severe wind gusts are classified primarily by the time of year in which they occur. Results from this study could be integrated into WSR-88D severe weather algorithms designed more specifically for the Florida environment.

1. INTRODUCTION

Kitzmiller, et al. (1992) noted the difficulty of producing a catch-all severe weather algorithm for the WSR-88D for the Florida environment. Precursors to the WSR-88D severe weather algorithms were developed for use with the WSR-57 RADAP augmentation many years ago. These algorithms assume cells with large areal extent are more likely to be severe than smaller cells with larger maximum VILs (Beasley, 1986). That is not always the case. The purpose of this study is to determine, primarily from RADAP II data, radar parameters and thresholds which may be associated with severe weather occurring in central Florida.

A total of 97 severe weather events in central Florida within 120 nm (220 km) of the Ruskin (Tampa Bay Area) WSR-57 radar site were examined. The study period was 1988 and 1989. RADAP II data were compiled for each case, at ten minute data collection intervals, from one hour prior to the event to one-half hour after the event. Reflectivity, VIL and echo top were examined. VIL is determined by summing the liquid water equivalent (kg/m^2) which is calculated from reflectivity values from successive two-degree radar antenna tilts, up to a maximum elevation angle of 22 deg.

VIL maxima, in 3 x 5 nm (5.6 x 9.3 km) blocks, were determined for each cell associated with severe weather. VILs of 50 kg/m^2 or greater were noted. If no VILs of at least 50 kg/m^2 were present, then highest VILs were noted. For each VIL observation (range bin), associated reflectivity and echo top (TOP) were also recorded. This was done for each ten-minute scan available.

2. BACKGROUND

Based on work by Squires (1958), Paluch (1979), and Emanuel (1981), Stewart (1991) related the RADAP II VIL divided by TOP relationship (which we will refer to as a density) to the cloud top penetrative downdraft mechanism. He showed that a 50 kg /M2 VIL with a 35,000 ft top (10,670 m) produces a 51.2 kt gust potential (resulting in a density of 0.0047 kg/m^3). This implies large mass high in the cloud. A 50 kg/m^2 VIL with a 50,000 ft (15,240 m) top produces a density of 0.0033 kg/m^3. This combination did not produce severe weather. He indirectly determined a density threshold for VIL and top combinations associated with strong gusts to be around 0.0040 kg/m^3. Greater densities lead to greater downward momentum transport and dry air entrainment, resulting in evaporative acceleration. This transport may interact on meso and microscales to produce vorticity, shear or other ingredients favorable for severe weather. Cell density appears to be the most important element in our central Florida study.

Our results confirmed the use of a cell density threshold of 0.0040 kg/m^3 as an indicator of severe weather. Eighty-three percent of all severe weather cases studied met this threshold. Eighty percent of the gust cases, 83 percent of the tornado cases and 86 percent of the hail cases had densities equal to or greater than the threshold of 0.0040 kg/m^3. This value appears to be a consistent indicator of severe weather regardless of individual VIL and top values. Appendix 1 illustrates these findings.

A second factor found to correlate well with thunderstorm severity in central Florida is the momentum of the system, calculated from the VIL (mass per unit area) and velocity. Faster moving, lower VIL thunderstorms are more often associated with synoptic scale systems and develop into the familiar bow echo (Fujita, 1978) or LEWP - line echo wave pattern (Nolen, 1959).

Positive and negative growth rates were calculated for VILs and TOPS and appear to be related to hail, tornado and wind gust occurrence. Beasley (1986) found significant top changes greater than 5000 ft (2400 m) in ten minutes, or VIL growth of more than 10 kg/m^2 in the same time interval, to be associated with severe weather (Appendix 1).

3. DISCUSSION

To understand how VIL, cell density, cell momentum and cell growth rates can indicate severe weather, the Florida severe weather climate was examined. Central Florida has two primary severe weather seasons; summer and winter. Most thunderstorms occur during summer (June, July and August), with May and September being transition months to the less active winter season. During summer a deep layer of tropical air usually exists over the state. Surface convergence is produced by seabreezes, land and water boundaries or outflow boundaries from existing convection. Doswell (1982) noted that a seabreeze alone is not strong enough to produce severe convection, but convergence can be enhanced over central Florida by combinations of the East Coast seabreeze with the West Coast seabreeze, and by interactions among seabreezes and outflow boundaries.

Phenomena that postpone development of convection, such as a strong inversion or a strong surface gradient wind opposing the seabreeze, can lead to explosive development when the capping inversion or gradient wind is finally overcome. Upper level forcing such as divergence, or destabilizing factors such as cold air aloft, may also enhance thunderstorm development. The experience of forecasters at WSO Tampa Bay Area (Ruskin) indicates the typical central Florida summer thunderstorm has a VIL of 45 kg/m^2, a top around 45,000 ft (13,700 m), and moves about 10 kt (5.1 m/s).

During winter, thunderstorms typically are associated with the southward extension of mid-latitude baroclinic troughs. Pre-frontal squall lines produce fast moving thunderstorms. Mesocyclones are more common during winter, and colder temperatures aloft are associated with hail occurrence. The typical central Florida winter thunderstorm has a 30 kg/m^2 VIL, a 25,000 ft (7620 m) top, and a speed of about 20 kt (10.3 m/s).

TORNADOES

Considering all of the tornadoes documented during the period of this study, thunderstorms which spawn tornadoes tend to move slower, 13.5 kt (7.0 m/s), have lower maximum VIL and TOP averages, have lower VIL growth and decay averages, and lower momentum averages when compared with thunderstorms which produce hail and wind damage. Most tornadic thunderstorms developed during summer. It is hypothesized there are three primary mechanisms for tornado formation in central Florida: the stretched vortex tornado, the gust-induced tornado, and the wintertime dynamic tornado.

Stretched Vortex Tornado

Wakimoto and Wilson (1989), and Brady and Szoke (1988, 1989) suggested that non-supercell tornadoes could when convection stretches low level vortices into weak, short-lived tornadoes. They mentioned the need for a low-level vortex, strong surface heating, light wind in the 6-10 km layer, a 20-35 dBZ increase in mid- and upper level reflectivity in five minutes, and rapid growth of the thunderstorm. The result was originally termed "landspout" by Bluestein (1985), after the resemblance to waterspouts.

In Florida, weak surface shear lines and vortices can occur where outflow boundaries merge, or at inflection points along boundaries, or near an orographically induced circulation from a seabreeze. Tornadoes occur in a capping situation in the early stages of convection during a period of rapid growth. The process is similar to dust devils, explained by Barcilon and Drazin (1972) as follows: in a region of horizontal shear Helmholtz instabilities create a line of vortex tubes which, when coupled with a rising thermal, stretch the vortex until it reaches tornado strength.

Thunderstorms associated with stretched vortex tornadoes can be characterized by:

1. New cells - less than 30 min old
2. Slow cell movement - 15 kt (7.7 m/s) or less

3. Moderate VIL - 50 to 60 kg/m^2
4. Fast growing VIL - 15 to 20 kg/m2 in 10 min
5. Moderate storm top - 50,000 ft (15240 m) or less
6. Fast growing top - 15,000 to 20,000 ft (4570 - 6100 m) in 10 min

Gust-Induced Tornado

Mueller and Carbonne (1987) found from their work on the dynamics of thunderstorm outflow that the dominant vorticity forcing term may be convergence resulting from downdraft spreading at the surface. Wilson (1986) looked at small tornadoes that form along wind shear lines and gust fronts and labeled them "gustnadoes." He noted these tornadoes originate in a zone of shear, possibly as shear-induced Helmholtz instabilities as discussed by Carbone (1983). Unlike stretched vortex tornadoes, gust-induced tornadoes form during the decay stage of a thunderstorm, when the cell is collapsing.

Thunderstorms associated with gust-induced tornadoes seem to exhibit a steady decrease in VIL about 10 minutes before the event. This is after a period of VIL growth from about 30 minutes before the event. Seventy-seven percent of the maximum VIL occurrences preceded a marked VIL decrease in the study cases. Storm top seems to peak 30 minutes before the event and is closely correlated with maximum VIL. Similar to straight-line wind gust events, occurrence of maximum VIL and the following collapse in VIL may be a precursor to tornado development. Vorticity at a boundary or shear line can be created by downrushing air associated with TOP and VIL decreases. Klemp and Rotunno (1983) defined an occluded, dynamically-driven downdraft as important for tornadogenesis along gust front storms, because it provides a mechanism for the concentration of surface vorticity.

Effects of gust-induced tornadoes look most like straight line wind gust events. Associated thunderstorms can be characterized as follows:

1. Large cells
2. Clusters of VILs greater than 50 kg/m^2
3. Maximum VILs 60 kg/m^2 or greater
4. Slow moving cells - 10 kt (5.1 m/s) or less
5. Primarily occur in summer

Wintertime Dynamic Tornado

Contrasting the rather stagnant summer patterns, during the cool season (October to May) convection generally develops from a combination of positive vorticity advection and divergence aloft, surface convergence from a frontal trough, and abundant low-level moisture. These conditions can produce large thunderstorms that are generally fast-movers (20 to 40 kt [10 to 21 m/s]). At times the atmosphere is less dynamic and convection is more subtle, perhaps embedded in a large area of rain. Although Fujita scale F3 to F5 tornadoes are rare over central Florida, as in other areas these major tornadoes typically last longer and are responsible for potentially more devastating effects. Associated radar echoes take on the characteristic shapes of the bow echo, LEWP and supercell.

Dynamic tornadoes in Florida are generally associated with lower VILs and faster moving cells. Although VIL is often below 50 kg/m^2 in dynamic tornadoes, cells move at 20 to 40 kt (10 to 21 m/s). During the study period, four apparent dynamic tornado events with VILs below 50 kg/m^2 produced momentum which averaged 477 kg/ms. Bow echo maximum tops are often ahead of the maximum surface echo (Fujita, 1978). This correlates well with the cell density average 0.0047 kg/m^3. In several of the small VIL tornado events, top growth was negative, indicating decay prior to the reported tornado.

Characteristics of thunderstorms associated with dynamic tornadoes are:

1. Fast moving cells - 20 to 40 kt (10 - 21 m/s)
2. Low VIL - 50 kg/m^2 or less
3. High momentum - above 450 kg/ms
4. Primarily occur during winter
5. Associated with LEWP, bow echo or supercell

One supercell was identified during the study period. It maintained strength while producing a tornado and one inch (2.54 cm) hail. The supercell's highest VIL (60 kg/m^2) was measured after damage time; however, preceding damage, VILs were in the 50 to 55 kg/m^2 level. The storm moved east rapidly at 30 kt (15.4 m/s).

DOWNBURSTS

During winter, thunderstorms associated with downbursts often form into a line and have VILs less than 50 kg/m^2. They move fast (more than 20 kt [10 m/s]), and have high momentum averages (653 kg/ms). These thunderstorms form primarily in a highly sheared environment that limits vertical development, but they are able to translate their momentum into surface winds through downdrafts. These thunderstorms typically exhibit slow change or evolution.

There is an inverse correlation in these storms between VIL and speed of motion. Faster moving cells generally have lower VILs. In 11 events with maximum VILs less than 50 kg/m^2, 91 percent exceeded the average speed of 16 kt (8 m/s), and 81 percent exceeded 25 kt (12 m/s). Implications of this are that speed shear may be a key mechanism for low VIL downbursts, via momentum transport to the surface through convergence.

Thunderstorms which produce winter downbursts have characteristics similar to the dynamic tornado:

1. Fast moving cells - 20 kt (10 m/s) or greater
2. Low VIL - less than 50 kg/m^2
3. High momentum - above 450 kg/ms

4. Winter occurrence
5. Associated with LEWP, bow echo or supercell

Summer wind events are characterized by VILs equal to or greater than 50 kg/m^2, speeds around 10 kt (5 m/s), and an average momentum of 429 kg/ms. Cell density in summer cases averaged 0.0044 kg/m^3, equivalent to a 65 kg/m^2 VIL with a 45,000 ft (13,700 m) top. Lower tops and higher VILs mean mass concentrated in the storm that will descend, entraining drier air and causing evaporation and acceleration of the descending air.

Eighty-one percent of the gust cases with maximum VILs greater than 45 kg/m^2 moved slower than average. Thus, VIL content (i.e., buoyancy and stability) may be more influential in larger storms. A review of cases showed that VIL and TOP typically increase until about 40 minutes before the downburst, followed by a brief decrease in growth. A weaker period of growth peaks 20 minutes before the downburst. This coincides with the average time of maximum VIL occurrence. Following this VIL peak, there is a steady decrease in VIL and TOP. This may very well signify downburst initiation. Thus, based on these findings, a 10 to 20 minute warning time may be possible.

Thunderstorms associated with summer downbursts are similar to those accompanying gustinduced tornadoes, namely:

1. Large cells
2. Clusters of VILs greater than 50 kg/m^2
3. Maximum VILs 60 kg/m^2 or greater
4. Slow moving - 10 kt (5.1 m/s) or less
5. Summer occurrence

HAIL

Hail cases comprised about half summer and half winter events during the study period. Because of the higher reflectivity of liquid coated ice, average maximum VILs where higher than in the tornado and gust cases (61 kg/m^2) and occurred an average of 21 minutes before hail was reported on the ground. For hail events, VIL clusters and VIL positive growth rates were higher than in the gust and tornado cases. One event had a VIL growth rate of 3.5 kg/m^2 per min. Maximum cell densities averaged .0049 kg/m^3 and occurred an average of 27 minutes before hail was reported. Average density was higher than in the gust and tornado cases, mainly because of high hail reflectivities (and therefore VILs).

Hail events were characterized by a period of rapid growth until about 40 minutes before hail was reported at the ground, then slight decay in VIL for about 10 minutes, followed by slight growth until the time of hail occurrence. Hail at the surface was followed by a rapid decrease in VIL. The highest VILs averaged 21 minutes prior to hail occurrence. This matches theoretical hail formation scenarios, with the rapid decrease in VIL corresponding with the release of mass as hailstones. Nearly 79 percent of maximum VILs in hail events occurred prior to hail occurrence. Maximum VIL seems to be an important indicator of hail occurrence, if correlated properly with storm growth rate.

During the study period, average tops were 48,000 ft (14,630 m) and occurred an average of 28 minutes before hail was reported on the ground. Average top growth (700 ft/min, or 3.5 m/s) and decay (880 ft/min or 4.5 m/s) were highest for hail events. Average speed (16.3 kt [8.2 m/s]) and average momentum (512 kg/ms) were higher in hail cases, mainly due to the number of faster moving wintertime cases, but high VIL (greater than 60 kg/m^2) events had much lower average speeds (6.3 kt, or 3.2 m/s).

In Florida, colder than normal 500 mb temperatures of -13 to -16C during winter and spring, and -9 to -11C during summer are a precursor to hail development. Biedenger (1984) noted a 500 mb temperature of -IOC associated with a major South Florida summertime hailstorm. Ordinarily, temperatures are in the -9 to -12C range during winter and -6 to -8C range during summer.

Significant hail appears to be associated with temperatures between the 18,000 and 24,000 ft (5500 - 7300 m) levels. Marwitz (1972) indicated thermal buoyancy at 500 mb (Lifted Index less than -4C) was conducive to hail in supercells. Byers and Braham (1949) found the maximum frequency of hail at mid-cloud levels near 16,000 ft (4880 m). Browning and Foote (1976) found hail formation at 16,400 to 32,800 ft (5000 - 10,000 m), then rising to 39,400 to 42,700 ft (12,000 - 13,000 m). The median peak reflectivity height associated with hail in New England was found by Donaldson (1965) to be near 23,000 ft (7000 m).

In this study, the lower VILs associated with hail occurred during winter months with cold temperatures aloft. A threshold was identified which appears to occur as a simple empirical multiple of VIL and average of 500 mb and 400 mb temperatures, thus:

$$|(T_{500} + T_{400})/2| \times VIL > 750 \Rightarrow \text{Severe Hail } (¾''+)$$

During summer a 50 kg/m^2 VIL may be common, but to meet the above hail threshold the temperature factor must be at least 15C. This would require temperatures, for example, colder than -9C at 500 mb and -21C at 400 mb. This is not common during the summer in central Florida. Typical average summer temperatures are -7C at 500 mb and -17C at 400 mb, resulting in a 500 mb to 400 mb layer average of only -12C.

4. CONCLUSIONS

An analysis of RADAP II data has shown the value of several WSR-88D-like radar-derived parameters for detecting severe weather in central Florida. As the WSR-88D becomes the standard for weather radar observations, a need exists for algorithms that will be compatible with the severe storm environment in Florida. This study has shown the importance of regionallytailored algorithms. Based on this study, severe weather algorithms for the WSR-88D tailored for the Florida environment might usefully include the following easily computed parameters.

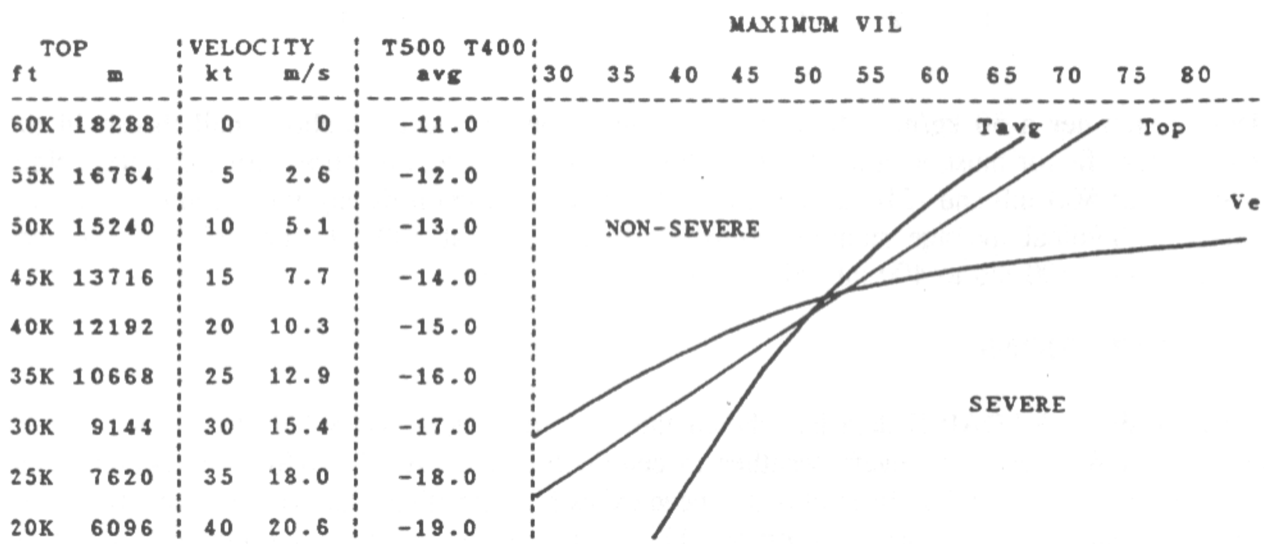
1. Momentum (VIL times velocity) for individual cells. Momentum exceeding 450 kg/ms indicates a high potential for downward momentum transport and shear. Of the tornado and gust cases with VILs less than 50 kg/m^2, 81 percent met this threshold.

2. Cell density (VIL/TOP). A density of 0.0040 kg/m^3 or greater indicates a good possibility for evaporative acceleration and downbursts, especially with a dry layer aloft. Of all severe weather cases, 81 percent met this threshold.

3. VIL growth rates. A positive VIL growth rate of 20 kg/m^2 or greater in a ten minute period, or a positive top height increase of 15,000 ft (4570 m) in ten minutes, indicates strong updrafts and/or rapid mass accumulation which frequently lead to severe weather.

   A VIL decrease of 20 kg/m^2 or more in ten minutes indicates a falling mass core, or a TOP collapse of 15,000 ft (4570 m) in the same time span may lead to severe weather. Forty-nine percent of the hail and tornado events we studied met these thresholds for rapid positive or negative changes. Only 29 percent of the gust cases met the thresholds, however, and most had VILs of 60 kg/m^2 or greater. The ten minute RADAP II sampling interval was likely too long to produce useful data in this case, but the shorter sampling time of the WSR-88D should better resolve rates of change.

Event severity did not correlate well with the parameters examined in this study, but most wind gust and tornado strengths were evaluate From damage reports. Estimates varied little in magnitude. Interestingly, 92 percent of the cases in this study met at least one of the severe weather thresholds listed above. Using maximum VIL, maximum reflectivity top, storm velocity and ambient 500 mb and 400 mb temperatures, the figure below can be a useful tool for discriminating severe from non-severe events.



No single radar parameter can delineate all severe versus non-severe storm events. However, we can recognize relationships among the various parameters. Namely, fast moving shallow convection with high VIL, embedded within a cold mid-tropospheric ambient air mass, is most likely to produce severe storms. Conversely, slow-moving deep convection with low VIL, embedded within a warm mid-tropospheric ambient air mass, is less likely to produce severe storms.

Now that certain severe weather parameters have been identified and indicate a high probability of detection, another study is under way to examine the associated false alarm ratio.

ACKNOWLEDGEMENTS

The authors wish to thank Dan Smith and Steve Lyons (NWS Southern Region Headquarters), Peter Ray and Bret Whissel (Florida State University), Paul Duval (NWS Tallahassee), and Robert Balfour (NWS Tampa Bay). This research was partially funded with a Department of Commerce Pioneer Fund Grant.

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APPENDIX 1. PARAMETERS EXAMINED AND RESULTS.

	GUST	TOR	HAIL
TOTAL EVENTS	56	22	19
VIL:			
MAX (average)	60.5	53.6	60.5
> 50 kg/m2 (%)	78.6%	72.7%	94.7%
30 TO 35 kg/m2 (%)	3.6%	4.5%	0%
40 TO 45 kg/m2 (%)	16.4%	22.7%	5.3%
50 TO 55 kg/m2 (%)	29.1%	27.3%	26.3%
60 TO 65 kg/m2 (%)	38.2%	45.4%	57.9%
>= 70 kg/m2 (%)	12.7%	0%	10.5
CLUSTER MASS (max/avg)	445/123	340/121	550/161
MAX (all cases)	80	65	80
MAX - time prior (min.)	27.6	27.7	21.3
GROWTH +/- (kg/m2/min)	.96/-.82	.85/-.69	1.11/-.77
TOP:			
MAX (average) (ft) (m)	43700 13320	43500 13256	47600 14508
MAX TIME (average)	28.7	30.2	27.9
GROWTH (avg max)(+/-)(m/s)	3.4/-3.1	3.5/-4.0	3.6/-4.5
DENSITY:			
MIN (kg/m3)	0.0024	0.0034	0.0034
MAX (kg/m3)	0.0069	0.0079	0.0076
AVG (kg/m3)	0.0045	0.0046	0.0049
AVG (VIL 30 TO 35kg/m2) kg/m3	0.0050	0.0000	0.0000
AVG (VIL 40 TO 45kg/m2) kg/m3	0.0066	0.0050	0.0055
AVG (VIL 50 TO 55kg/m2) kg/m3	0.0044	0.0041	0.0048
AVG (VIL 60 TO 65kg/m2) kg/m3	0.0044	0.0049	0.0049
AVG (VIL >= 70kg/m2) kg/m3	0.0044	0.0000	0.0046
>= 0.0040 kg/m3 (%)	79.6%	80.9%	83.4%
< 0.00360 kg/m3(%)	7.4%	9.5%	5.6%
0.0036 TO 0.00399 kg/m3 (%)	13.0%	9.5%	11.1%
0.0040 TO 0.00439 kg/m3 (%)	40.7%	38.1%	27.8%
0.0044 TO 0.00480 kg/m3 (%)	18.5%	19.0%	5.6%
> 0.00480 kg/m3 (%)	20.4%	23.8%	50.0%
MAX - time minutes	31.3	37.2	26.6
MOVEMENT:			
avg speed (kts / m/s)	16.0 / 8.2	13.5 / 7.0	16.3 / 8.4
MOMENTUM:			
avg kgm/s	438	360	512
VIL < 50 kg/m2 (kgm/s)	653	429	N/A
VIL 30 TO 35 kg/m2 (kgm/s)	378	360	N/A
VIL 40 TO 45 kg/m2 (kgm/s)	721	442	N/A
VIL 50 TO 55 kg/m2 (kgm/s)	355	318	707
VIL 60 TO 65 kg/m2 (kgm/s)	354	345	480
VIL >= 70 kg/m2 (kgm/s)	580	N/A	267